GIS-Based Engineering Management Service Functions: Taking GIS beyond Mapping for Municipal Governments

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Abstract: A geographic information system (GIS) is found to be a platform of choice for meeting the needs of several core engineering functions. However, there is a dearth of GIS usage for engineering management service functions (EMSFs), which typically are specific to individual jurisdictions. This study outlines a simple approach for automating EMSFs on a GIS platform and demonstrates its efficacy. In the first phase of this research, a review of GIS applications in various municipal government functions is conducted. The review indicated that most municipal governments have currently employed GIS for a variety of general administrative services such as revenue collection, data archival, and information dissemination purposes. The proposed approach is demonstrated by developing a GIS model for a sanitary sewer reimbursement (GIS-MSSR) program at a fast-growing urban municipality. Data modeling issues related to representing complex management tasks within the context of a relational database model are discussed. Development of functional requirement specifications for GIS models and their implementation are also discussed. The effectiveness of the approach is verified by highlighting productivity gains resulting from the development of GIS-MSSR. The research concluded that several complex engineering service management functions can be automated on GIS platforms to realize substantial productivity gains. Automating multiple tasks, however small they might be, in an integrated environment can increase the productivity even further.

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Background

Local municipal government bodies such as city councils and county boards play a pivotal role in providing services to citizens and regulating urban development. Most municipal governments use geographical information systems (GIS) for a variety of general services such as revenue, archival, and information retrieval purposes. As would be expected, the extent of GIS use varies significantly among municipal governments within a state and across the country. Even for jurisdictions that maintain an exhaustive set of data for GIS purposes, the extent of GIS uses within many divisions of that government can be vastly different. In general, penetration of GIS is more prevalent in performing administrative tasks than conducting engineering analysis, design, and management. Since many of these routine tasks are specialized and specific to the local jurisdictions, a limited set of off-the-shelf tools is available to meet the needs of these tasks. Furthermore, the intricacy of analytical steps involved in infrastructure management tasks coupled with the complexity of associated engineering computations is a deterrent to developing custom solutions at resource-strapped local governments.

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This study deals with a structured approach for automating engineering management processes on a GIS platform. The approach is focused on treating GIS solution development as an operating expense rather than capital expenditure. The study methodology is demonstrated via integrating a sanitary sewer reimbursement program on a GIS platform in Fairfax County, Virginia, which is a fast-growing urban municipality. Principal objectives of the study are to

1. Conduct a review of GIS use for engineering services management among municipal governments across the United States;
2. Outline a simple approach for developing GIS-based applications for automating engineering management functions;
3. Develop a GIS model to demonstrate the effectiveness of the methodology; and
4. Provide a comparative assessment of a GIS-based model over manual procedures in terms of productivity measures.

It should be pointed out that the research presented in this paper is applied in nature and is aimed at increasing the use of GIS for meeting the needs of engineering management service functions (EMSFs) by municipal governments.

GIS Applications for Engineering Services Management

Environmental Systems Research Institute (ESRI) (2005) provides an insightful and thorough overview of a number of GIS applications in various municipalities around the world. A close scrutiny of these applications indicates that various local governments use GIS predominantly for mapping, administrative, and information dissemination purposes. In many engineering departments at the local level, GIS is primarily used as a depository of

data on infrastructure such as road and utility networks and as a tool to conduct perfunctory analysis to query and synthesize existing data. Certain municipalities have adopted the use of GIS-based custom tools to conduct core engineering functions (CEFs) such as design and analyses.

Engineering management service functions (EMSFs) differ from CEFs in one significant way. Usually, CEFs reflect nationwide engineering practices and are not specific to local jurisdictions, whereas EMSFs are infrastructure management practices that are specific to individual jurisdictions, and steps in a typical EMSF include one or more CEFs. A review of the literature on the computing component of CEFs indicates that well-defined engineering tasks are performed with the help of domain-specific software, GIS, and custom spreadsheet applications. For example, CEFs such as capacity analysis and study of hydraulic behavior in water distribution and sewer networks can be performed using such commercially available stand-alone or GIS-based modeling software as SewerCAD, Eagle Point, Hydra, Mouse, MIKE SWMM, and InfoWorks (Baik 2004).

In recent years, there has been increased emphasis on developing solutions for CEFs on GIS platforms (Abudayyeh et al. 2004; Joshphar et al. 2005; Bowman 1998). Miles and Ho (1999) raised an awareness of the issues related to GIS-based modeling in civil engineering modeling. The paper also highlighted the potential for the misuse of GIS in the context of engineering modeling and suggested that this potential can be reduced through education and awareness. Preusch and Rezakhani (1999) discussed issues related to the integration of GIS and watershed modeling and indicated that GIS is used to preprocess watershed data, delineate watershed boundaries and drainage areas calculated from a digital elevated model (DEM), generate runoff curve numbers (RCNs), and develop and display runoff hydrographs.

Denning (1993) has discussed the potential of GIS to drastically change the way municipal and state-employed engineers work on roads, water systems, sanitary engineering, and planning issues. With the availability of GIS on desktop computers since the mid 1990s, the penetration of GIS in small government functions has increased (Borchardt and Tonias 1996). Sanghavi and Mattejat (2003) enumerated different ways of managing statewide storm-water best management practices (BMP) facilities in the state of Maryland. The article does not provide insights into managing sewer systems at the local level. Herzog and Labadie (2000) discussed the importance of GIS in reducing costs of installation, expansion, and maintenance of storm and wastewater management systems. Storm-water and wastewater administration applications discussed include maintenance, hydrologic modeling, flood control, and storm-water quality. Murphy (2000) outlined the newest technological developments in GIS and how they affect civil engineers. Technical issues related to hardware, software, and data management were discussed. The use of GIS for transportation infrastructure development and management is prevalent (Turton 2003). Most transportation engineering management applications at the state level are related to pavement management. In jurisdictions where pavement management is entrusted to municipal governments, the use of GIS for these functions in limited. Stidger (2002) discussed major issues related to managing transportation system by municipal governments.

In general, engineering departments in most municipal governments use GIS in combination with specialized software (e.g., Water CAD) for meeting the needs of certain well-defined analytical tasks such as watershed analysis and management. For example, the county engineer's office of Lancaster County, Pennsylvania, prepares state-mandated Act 167 storm-water management plans for watersheds within the county using GIS in combination with storm-water modeling software (Lancaster County 2005). The concept behind the plans is to address storm-water and flooding issues on a regional basis. Additionally, in Medina County, Ohio, a GPS monumentation project was initiated in 1998 to establish a countywide coordinate system that would enable the sanitary engineers to geographically locate water and sanitary utilities for mapping purposes. (Pritchard 2005). At present, Medina County does not use these GIS data for engineering management purposes.

Baik (2004) conducted a short survey of state of the practice among county governments throughout the United States. The purpose of the survey was to identify, at the county level, certain general issues related to EMSF and some specific issues related to using a GIS platform to perform sanitary sewer management functions. Representatives of the following county/municipal governments were first contacted via e-mail about the intent of the project as follows:

- Jefferson County, Alabama;
- Oakland County, Michigan;
- Fairfax County, Virginia;
- City of Fairfax, Virginia;
- Loudon County Sanitary Authority, Virginia;
- Prince William County, Virginia;
- Sanitation Districts of Los Angeles County, California; and
- King County, Washington.

The respondents were later followed up with phone calls. However, appropriate technical persons at each agency were interviewed in such a way that their expertise on issues specific to this research is adequately summarized. The following is a summary of the review of state of the practice related to EMSFs in these counties:

- Many municipal agencies are using GIS for a variety of applications. However, most engineering analytical tasks are performed using software designed for domain specific applications.
- Public works departments in each of these counties are responsible for several EMSFs to maintain and manage infrastructure facilities. Practices related to EMSFs such as sanitary sewer management vary significantly across municipalities.
- The perception among the analysts at the agencies contacted in the survey is that it is very difficult to represent many business processes involved in EMSFs as data models that are consistent with GIS.
- Most municipal government officials (mainly technical personnel) contacted for this review recognized the potential for GIS-based business processes to improve productivity.
- The officials also expressed a strong desire to automate within a GIS environment as many engineering functions as possible. However, due to various constraints, many of which have been identified by Przybyla (2002), the penetration of GIS for these functions is found to be limited.

The survey also indicated that several technical and financial issues impede the adaptation of GIS for the needs of CEFs and EMSFs. Currently, the needs of many EMSFs are still met by traditional mechanisms such as manual computations and crude automation tools. Due to financial considerations as well as the seemingly complicated nature of many such tasks, the potential for using GIS for these functions has not been exploited. Furthermore, most municipal governments treat the development of GIS-based solutions as a capital expenditure, which subverts the justification for developing GIS-based solutions for these seemingly smaller, albeit numerous, tasks.

Przybyla (2002) cited Waterford Township, Michigan, as an exemplary municipality where most township departments use GIS for solving a variety of engineering problems. These solutions range from computerized maintenance and management of sewer and water facilities and services through addressing land-use zoning questions. Przybyla also outlined the following seven major obstacles to successful implementation of GIS in public works functions:

1. The need for quantitative definition of financial payback at the beginning of the project;
2. Lack of vision or plan for GIS;
3. Treatment of GIS solely as a technology issue rather than a people issue;
4. Internal organizational barriers or other bureaucratic hurdles;
5. Balancing between hiring and retaining the right personnel and outsourcing a project;
6. Budgeting; and
7. Treatment of GIS as a capital expenditure and not as an operating expense.

While certain common practices do exist among counties, the potential for developing a single GIS solution that will serve the functional needs of many counties is minimal. Varying levels of GIS-related knowledge and skills among policy makers, management, engineers, and GIS analysts and a communication gap among these constituents further compounds the complexities of adapting GIS for CEFs and EMSFs.

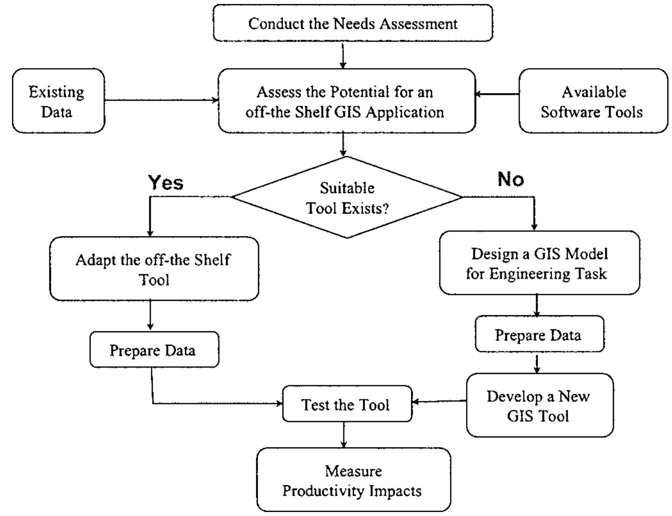

Fig. 1. Schematic representation of the research methodology

Study Approach and Methodology

The review of state of the practice at various public works departments indicated that policy makers, management, engineers, and GIS analysts could benefit from a study that highlights a structured approach to developing GIS-based solutions to EMSFs. The approach should address various issues related to developing GIS solutions for engineering functions. That is, issues ranging from providing a reasonable justification for the development of the GIS model to addressing various computational complexities associated with model development must be addressed in the proposed approach. In this section, a structured approach to adopting GIS for EMSFs is outlined. This approach is focused on overcoming the seven obstacles outlined by Przybyla (2002). A schematic representation of the approach is presented in Fig. 1.

The methodology does not call for an a priori cost-benefit analysis of the development of GIS applications, but rather treats GIS as an operating expenditure and not as a capital expense. In most cases, the need for developing a GIS tool for EMSF may be qualitatively justified based on one or more of the following factors.

- The process involves at least one subprocess or component that requires spatial analysis;
- The process comprises a series of complex and/or manual computations that could result in many errors;
- Steps in the process are repetitive in nature;
- The demand for the services involving the process is moderate to high; and
- A significant amount of engineers' time is diverted to meeting the demands of engineering management.

Once a decision on acquiring or developing a GIS tool for the task is made, a careful review of existing data such as GIS layers and other ancillary data should be conducted. This review can save significant amounts of time and effort as opposed to gathering data from ground zero. In addition to the available data layers, the task may require additional data items related to the processes specific to the task and the local regulations governing these processes. Restrictions on the lot size of dwelling units within certain zones may be cited as an example of regulations governing the process of issuing housing permits for new construction. Suitability of commercially available application programs or software tools should be evaluated. These tools can be classified in two broad categories:

- Core GIS application software, developed and distributed by GIS vendors such as Environmental Systems Research, Inc. (ESRI); and
- Domain-specific analytical tools that may or may not be based on GIS platforms.

The main advantages of core GIS software include the capability of producing quick visual display of spatially related data and facilitation of elementary analytical tasks such as spatial and network analysis. However, nontraditional GIS tasks require additional development efforts within the GIS platform. It is essential to examine the capabilities of available tools and the scope for adopting these tools to suit the needs of the given EMSF. Should a suitable off-the-shelf custom application be available, it is highly desirable to acquire and adopt that tool to meet the computational and administrative needs of the EMSF. If no suitable tool exists, a GIS model is developed on a suitable platform. The GIS model should also be subjected to a series of tests to ensure accuracy of the final output. At a minimum, the results of manual analysis at various steps should be compared vis-à-vis results of the GIS model. Thus, the following important issues should be sorted out before a GIS model can actually be developed:

- Which data items pertinent to the task are currently available?
- Which additional data items are required and how might these be collected and compiled?
- What type of off-the-shelf application tools, GIS based or not, are available that can be adapted to serve the needs of the task?
- If no off-the-shelf application tools are available, what is the feasibility of developing a solution on a GIS platform? In other words, what are the internal resources available to develop a custom GIS solution to meet the needs of a given EMSF?

- What will be the optimal relational data model of the GIS solution and how might the data items be put together for the GIS model?
- What will be the functional specifications of the GIS model?
- Which development environment best suits the data model and what are the development-related issues?
- How do the solutions provided by a GIS model compare to the results of manual operations?
- What are the productivity implications of automating the task in a GIS environment?

Effectiveness of this methodology may be demonstrated by examining the needs of EMSF for utility infrastructure management at local governments.

Utility Infrastructure Management at Municipal Governments

Utility networks are part and parcel of GIS data layers in many counties and other municipal governments. To establish the importance of developing GIS-based solutions to the needs of engineering management tasks, the complexities associated with managing utilities infrastructure are discussed in this section.

Typical computing challenges in fast-growing urban areas range from such tasks as maintenance and management of existing utility networks to providing utility services to newly developed neighborhoods. Usually, meeting the needs of core engineering functions (e.g., design and construction) for utilities such as electric power, water, and waste water distribution systems is relatively straightforward. Several off-the-shelf computer-aided design (CAD) and GIS solutions exist to meet the needs of most CEFs. However, the same cannot be said about the EMSFs. Due to scarcity of financial resources, municipalities are resorting to innovative financial mechanisms for building new service facilities such as trunk power, water, and sewer lines. Furthermore, connecting new service facilities to the existing networks or privately financed trunk lines and getting reimbursed for the new service is often a challenging engineering management problem.

When new housing or commercial developments are built, the utility services are tapped into the existing network. When the privately sponsored utility lines are being tapped into by these new developments, the municipal jurisdiction has the obligation to reimburse the entities that sponsored the construction of utility lines. Usually, such reimbursement processes are based on complex sets of rules that take a variety of variables into consideration. For example, electric utilities are highly regulated in many states. Should a new service request be made for a new housing development project that is located far away from existing developments, only certain portions of the cost of laying the new electric transmission lines can be charged to the developer. Similar rules govern the reimbursement process for the new lines for sanitary sewer and water distribution lines.

As would be expected, the rules governing the reimbursement process for any new utility service need to be worked into a network modeling framework. For example, in cases involving determination of sanitary sewer reimbursement, the sewer sections that are subject to reimbursement need to be identified within the network of sewers. In most cases, the reimbursement estimation is requested several times until developers/contractors actually pay for the charge, which means that each time a new estimation is prepared, the same exercise needs to be repeated. This is why it has been difficult to obtain reimbursement estimation from public agencies. Most of the time, plan review engineers perform the reimbursement estimations. In addition to performing design verifications, a review engineer's normal duties include reviewing plans; yet a disproportionate amount of plan reviews still greatly disrupt the engineer's other routine tasks, thereby affecting the plan review schedules as well.

In most municipalities, the plan review engineers are often assigned these reimbursement tasks but these are not included in the normal duties of the engineer. The plan review engineer maintains and provides accurate calculations each time a request for information and estimated reimbursement is made. Because of its complexity and the turnaround time associated with such processes, these services are usually offered on a limited basis. Automating reimbursement estimation will improve efficiency of the plan reviewer's task management, the level of public service, save time, and provide accurate estimation every time. A solution based on a GIS platform that incorporates various elements of the plan review process can provide an efficient engineering management tool to achieve this goal.

Sanitary Sewer Reimbursement Systems

Issues related to sanitary sewer management and reimbursement programs vary with type of municipal area (Baik 2004). That is, for mature municipalities with low to moderate growth, the principal focus will be on the maintenance of existing facilities. On the other hand, fast-growing municipalities face challenges related not only to maintenance but also to expanding services to newly developing neighborhoods. To illustrate these differences, sanitary sewer management programs in a mature municipality (Los Angeles County, California) and a fast-growing urban county (Loudon County, Virginia) are discussed (Baik 2004).

The Sanitation Districts of Los Angeles County are a confederation of independent special districts serving about 5.4 million people in the county. The agency is made up of 25 separate sanitation districts working cooperatively under a joint administration agreement with one administrative staff. The agency's 1,300 mi of main trunk sewers and 11 wastewater treatment plants convey and treat approximately 530 million gal per day (mgd), 190 mgd of which are available for reuse in the dry southern California climate.

Reimbursement programs by sanitation districts are offered when a developer wants to install a sanitary sewer system that will be utilized for the future sewer services for others and wants to get reimbursed for the extra construction cost for the sewer installation. Undeveloped land is scarce in the mostly urbanized southern California. If developers propose to connect to the sanitation district's trunk line, the agency can negotiate the sewer size to accommodate future needs. During the negotiation, the sanitation district pays the difference in construction cost to upsize the new sewers. GIS is an essential tool to manage the entire sanitary sewer infrastructure system in Los Angeles City, but GIS is not part of the sanitation district's sanitary sewer reimbursement program.

Loudon County (Virginia), the fastest growing county in United States per the 2000 census, has a sanitary sewer reimbursement program that is conducted on a case-by-case basis. Included among the two types of improvement programs in Loudon County are capital-funded improvement projects and developer-funded projects. Capital-funded improvement projects are budgeted and funded by the Loudon County Sanitation Authority (LCSA) and constructed by contractors. Developer-funded

projects are very similar to the reimbursement program that sanitary sewer system installation is funded by the developer and the future users pay a prorated share as new service is connected to the sewer system.

LCAS currently does not utilize GIS to manage sanitary sewer reimbursement contracts but reimburses the original developer, who installs the sanitary sewer system with private funds in a 10-year time frame without interest. The future customers pay availability fees during permit processing time. If the future connection is made directly to the existing system, a local facility fee is assessed in addition to the availability fee. If a sanitary sewer system is extended from the existing sewer, there is no extra local facility fee. The LCSA sanitary sewer reimbursement program is maintained today as it was years ago, and files are kept in hard copy. Since GIS is a relatively new technology for Loudon County, no GIS model is available for maintenance of a sanitary sewer network or management of a sanitary sewer reimbursement program.

Sanitary Sewer Reimbursement in Fairfax County, Virginia

The sanitary sewer reimbursement program in Fairfax County—a neighboring county to Loudon County—is an EMSF aimed at innovatively financing major infrastructure development projects in this fast-growing county. The county offers the sanitary sewer reimbursement program to developers on a case-by-case basis. At the time of this study, the county maintains 28 active agreements related to privately sponsored sewer mains. The county's sanitary sewer reimbursement agreements authorize the county to collect the prorated share cost from the future customers and reimburses the original sanitary sewer infrastructure builder in a 20-year period. That is, the original developer will be reimbursed during the ensuing 20-year period from the sewer system acceptance date, or the agreement will be fulfilled if the construction amount is paid in full. Prior to this research effort, the county maintained and managed the sanitary sewer reimbursement agreement program manually with the help of spreadsheets and data tables.

As a plan reviewer receives plans for appraisal, the review engineer checks the tax map grid and general construction area. During the plan review process, the sewer connection point (sanitation outlay) is identified, and the existing sanitary sewer will be traversed on the paper map to check if any part of the downstream sewer is subject to reimbursement charges. A sewer-traversing task is similar to a network pathfinding problem with one exception—flow can happen only in one direction, that is, downstream. The review engineer follows the sanitary sewer map until the downstream sewers are clear of any reimbursement boundary or junction point.

If the proposed sewer is going through the existing sanitary sewer that is already subject to reimbursement, the engineer prepares specific worksheets. These worksheets show sections of sanitary sewer reimbursement, and the review engineer requires performing sewer unit conversion. The unit is converted to a single residential house usage equivalent based on four members in a house. This equivalent usage is called a "call-one" unit, and it is equivalent to 370 gal of wastewater per day. All other land usage is converted to equivalent single dwelling house units by using a conversion table that shows water usage estimation. These conversion tables are adapted from the Virginia Commonwealth's sewage collection and treatment regulations.

For example, if a developer is building a 200-townhouse community, and the wastewater from these townhouses is going through a sewer that is subject to reimbursement charges, the review engineer will multiply 300 gpd with 200 townhouse units. The product is then divided by 370 gpd to convert to single house units. After computing the single house units, the review engineer adds the section amounts, depending on how many different sections of existing sanitary sewer the proposed townhouses' wastewater goes through. The summed amount multiplied by the converted house unit will be the principal reimbursement amount.

It is a practice in Fairfax County to add 10% interest to the principal reimbursement. After the principal reimbursement is calculated, the review engineer counts the number of months from the acceptance date to the current date and divides the total months by 12 to get the number of years. The product of principal amount times 10% times the number of years will be the applied interest. The interest will be applied for the first 15 years only, which means that the reimbursement amount will be the sum of the principal amount and interest up to 15 years; the amount does not change after the 15th year until the agreement expires after the 20th year.

After this worksheet is completed, the review engineer passes the work to another engineer to ensure that the calculations are done correctly. Once the calculation is checked, the review engineer prepares a letter to the plan-submitting developer for sanitary sewer reimbursement notification.

When the submitted plan has been approved and the project is built, the developer is required to apply for a building permit to make the physical connection to the existing sanitary sewer system, and it is the time the developer needs to pay exact reimbursement charges. At this point, the county's account and revenue section recalculates an exact amount with a computer program, which was developed in the COBOL language. Once a year, the collected reimbursement charges are reimbursed to the original developer who signed the reimbursement agreement and built the sanitary sewer infrastructure system.

Need for Automating the Reimbursement Process

While the county does not have any financial stake in the program, due to the technical nature of the task and the computational complexities involved, it is currently performed by the plan review engineers. When a reimbursement request is filed with the county, the engineers meet the request when they are not engaged in other routine engineering tasks for which the county has primary responsibility. When dispensed to the task, the engineers collectively spend about 2 h for a typical sanitary reimbursement request. In a given year, 100 to 150 such reimbursement requests are filed with the county. It is widely believed that the number of requests would be much higher if the turnaround times for the filed requests were faster. Furthermore, current manual operations subject the process to potential errors that could result in errors to the tune of hundreds of thousands of dollars.

Owing to the time demands on technical personnel performing this task and potential errors in manual computations, the potential exists for this process to be fully automated with the help of GIS databases. However, the county was reluctant to devote resources to develop a GIS solution to automate this program for two reasons. First, the development process was seen as a capital expense and the economic benefits of automation, if any,

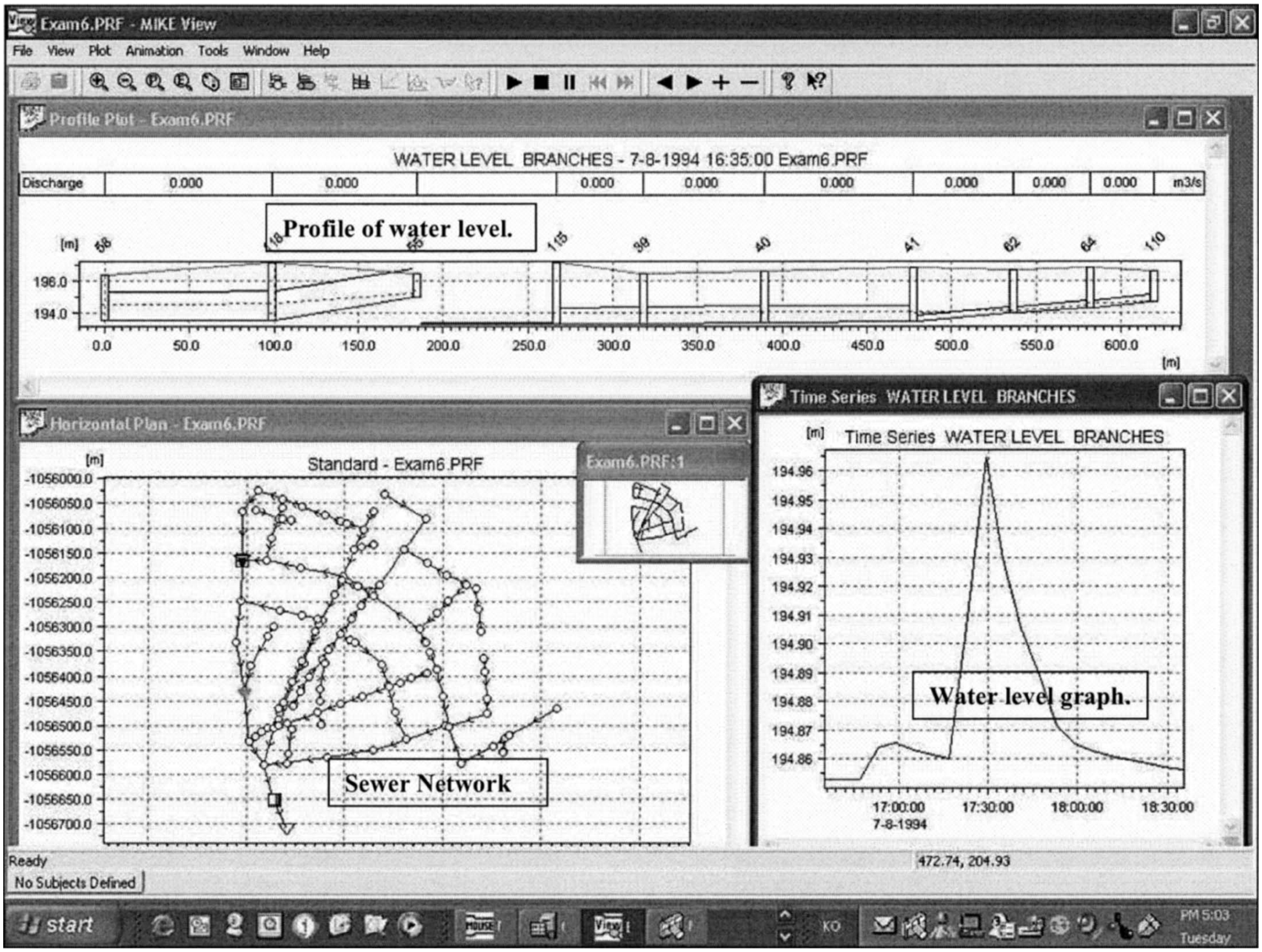

Fig. 2. MOUSE sanitary sewer modeling

perceived to be minimal, and second, the steps involved in the process were seen as complex and not compatible with typical GIS functions performed by the county.

Subverting the status quo, this research was undertaken by justifying the need for automating the process on two simple qualitative grounds: (1) to reduce turnaround time; and (2) to eliminate human error.

Software Evaluation

A thorough review of existing GIS-based software tools was conducted to evaluate the suitability of existing software to meet the needs of the sanitary sewer reimbursement program. The purpose of this review was to accomplish the automation task with minimal budget and effort. Different types of software applications were evaluated. Generally, certain analytical tasks related to water distribution and sewer networks are performed using network models that incorporate fluid dynamics analyses. Many such applications are developed either as stand-alone graphical models or as add-ons to a generic GIS platform such as ESRI's ArcView.

Certain static and dynamic modeling programs are being used to model hydraulic modeling for storm, sanitary, and water management. In most cases, GIS data layers are either integrated or embedded into the stand-alone modeling software. One of the most critical analytical tasks for a sanitary reimbursement program is the ability of the model to conduct network modeling such as pathfinding and capacity-restrained flow modeling. The review of existing software indicated that almost all of the commercially available sewer systems modeling programs have the capability of integrating with GIS and have built-in network analysis capability.

Included among the review of modeling software are static modeling tools such as SewerCAD, EaglePoint, and Hydra, which facilitate modeling of fluid flow capacity (Baik 2004). Fully dynamic tools such as Mouse, MIKE SWMM, MWH, and INFOWORKS were also evaluated (Baik 2004). These modeling tools have some common features such as hydraulic behavior and capacity analysis. The main difference between static and dynamic modeling is with respect to the flow diagram. In static modeling, the flow diagram is the same for all situations, but in reality the flow diagrams change due to head loss and friction and with time. Therefore, the dynamic modeling programs provide more realistic facility planning to save from oversizing and overbudgeting. (i.e., economic and engineering solution).

To evaluate the application tools for the purpose of the sanitary sewer reimbursement program in Fairfax County, full functional

Table 1. Entity Descriptions in the GIS Model for Sanitary Sewer Reimbursement

Entity/table/layer (type)	Short description	Comment
Sewer lines (SEWERLINE)	Existing network of sewers defined by upstream and downstream manhole structures	Countywide GIS (line) layer available
Manhole structure (STRUCTURE)	Existing manholes in the sewer network	Countywide GIS (point) layer available
Reimbursement contract (REIMBURSE)	Paper archive of existing contracts with developers who are beneficiaries of reimbursement program	Data to be tabulated and added to the system
Reimbursement pipes (REIM_PIPE)	Paper archive of existing sewer trunk lines subject to reimbursement when tapped into by new constructions	Data to be tabulated and added to the system
Land use (LANDUSE)	Spreadsheet of reimbursement rates that vary by type of land uses	Data to be added to the system

Table 2. Staff Resource Requirements for Sanitary Sewer Reimbursement Task

		Time requirement		
Staff title	Task	Manual (min)	GIS tool	Rate/h[a]
Engineer II	Estimate and prepare notification	60	5 min	$34.90
Engineer II	Checking calculation	20	Nil	$34.90
Engineer Technician III	Recalculation during permit processing	30	Nil	$30.29
Engineer Technician II	Collection	15	15 min	$25.16

[a]Fairfax County, Va.: 2004 average pay rates.

demonstration programs were installed and tested. Both InfoWorks and MOUSE are capable of performing very complicated real-time analytical functions as well as extensive network analysis (Fig. 2). In these models, tracking upstream and downstream sewer branches was a very quick and smooth operation, and identifying overflow sections was a simple task for both programs. However, none of these static and dynamic modeling programs provide mechanisms to integrate the sanitary sewer reimbursement program. Owing to this main limitation of the commercially available off-the-shelf sewer network modeling programs, the development of a GIS model for sanitary sewer reimbursement (GIS-MSSR) task is seen as a viable alternative.

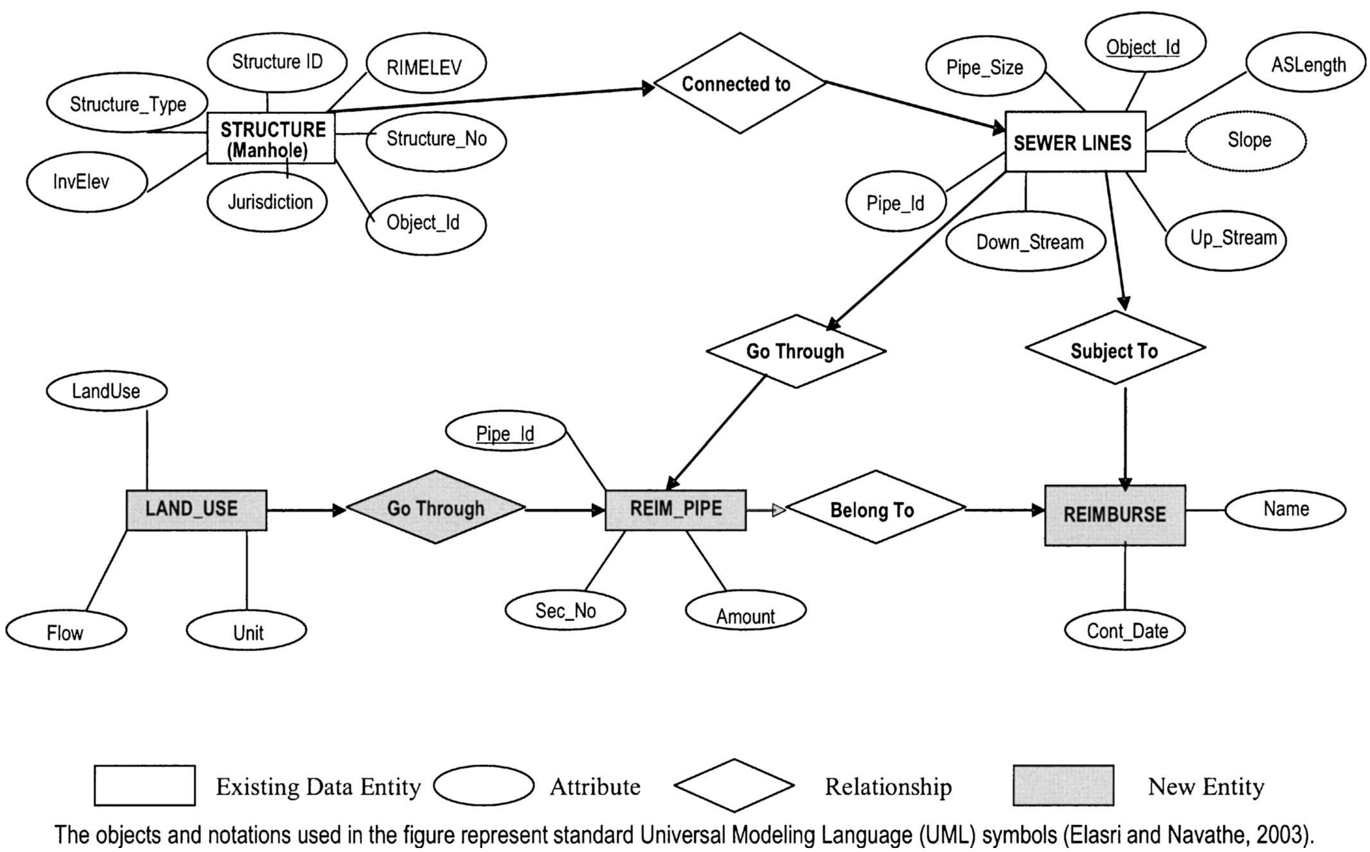

Fig. 3. Data model for GIS-MSSR

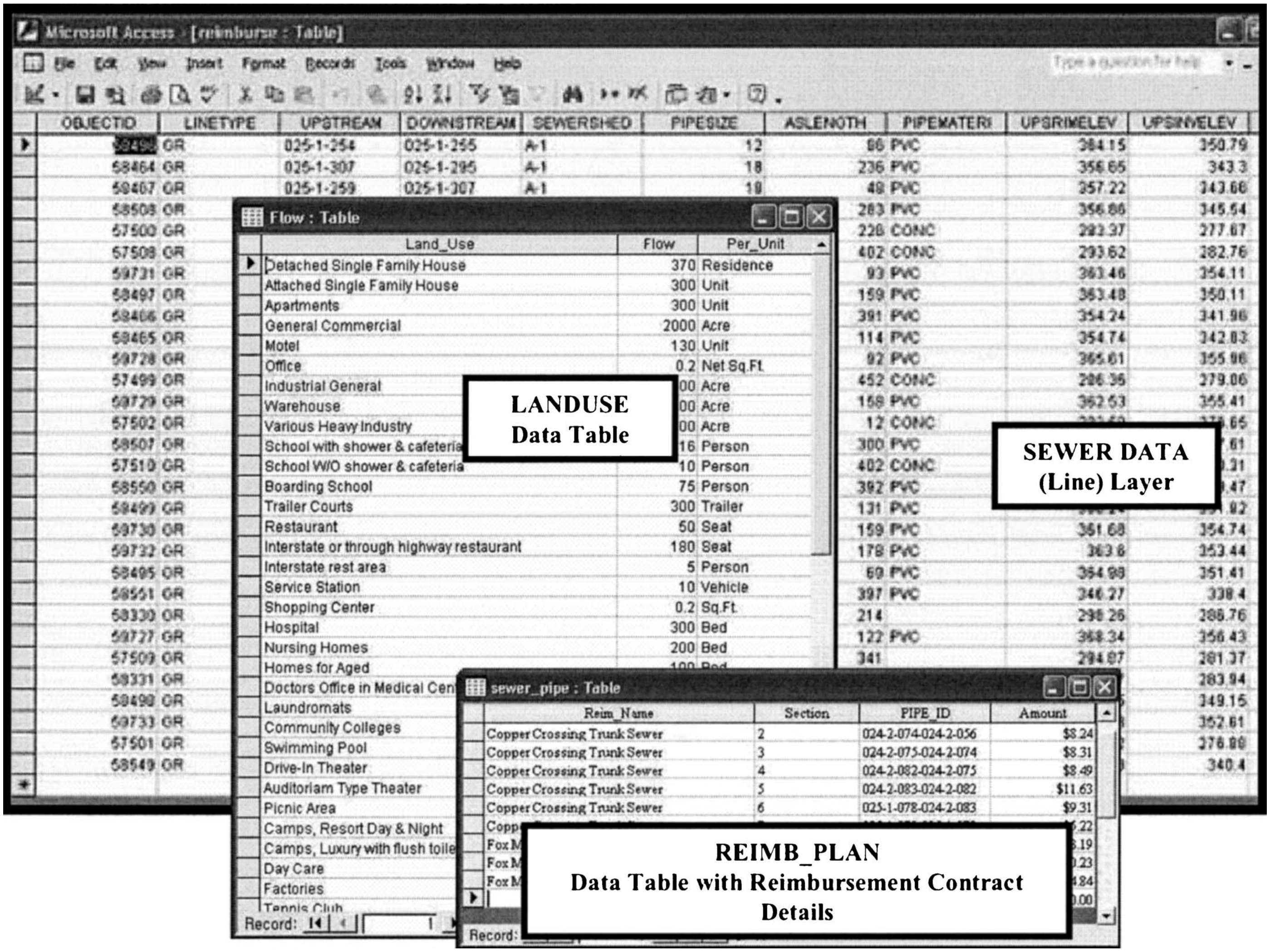

Fig. 4. Critical data entities in GIS-MSSR

GIS Model for Sanitary Sewer Reimbursement

ArcView (version 8 and later) offers the flexibility to develop external modules and integrate them with other GIS applications. Incorporated inside the ArcView development environment is the Visual Basic application development (ESRI 2005). For this reason, ArcView 8.2 is selected as the platform on which the sanitary sewer reimbursement program will be automated.

Data Model for GIS-MSSR

Representing management tasks as data tables related to GIS layers is perhaps the most complicated step in the development process. At a minimum, the management task has to be decomposed into database tables that have at least one common attribute with a GIS layer and/or other data tables. Data pertinent to sanitary sewer system mapping and reimbursement management are listed in Table 1, and the attributes of each of the entities listed in Table 2 are detailed by Baik (2004).

Currently, sewer data tables and GIS layers exist in Fairfax County for sanitary sewer, manholes, approved sanitary sewer service area, 400 ft administrative rule overlay, sewer sheds, pump stations, and force mains. The sanitary sewer network layer (SEWERLINE) and manhole tables (STRUCTURE) are essential for calculating reimbursement charges. From the SEWERLINE data table, pipe_id is the primary key for each sanitary sewer segment, and it is connected to STRUCTURE data table's structure_id as upstream and downstream manholes. Each manhole is a node point in the entire sewer system database, and therefore any new proposed sanitary sewer is connected at a manhole, which then facilitates modeling through one of the existing sewer pipe segments.

Representing the entire reimbursement process as tables in a relational database setting posed a challenge. Details such as year of contract, original cost, reimbursement rate, etc., on existing reimbursement contracts with developers are represented as the table REIMBURSE, and details on the pipe segments subject to reimbursement are represented as the table REIM_PIPE. As would be expected, not only are REIMBURSE and REIM_PIPE related to each other, but these tables are related to the existing sewer network table SEWERLINE by pipe identification pipe_id as the foreign key. As the reimbursement is dependent on the land-use classification of the pipes subject to reimbursement, a separate table LANDUSE is created and linked to the ERIM_PIPE table. The entity-relationship diagram presented in Fig. 3 illustrates the nature of attributes and the interrelationship of the above entities/tables. A screen capture of the data tables for these critical entities is shown in Fig. 4.

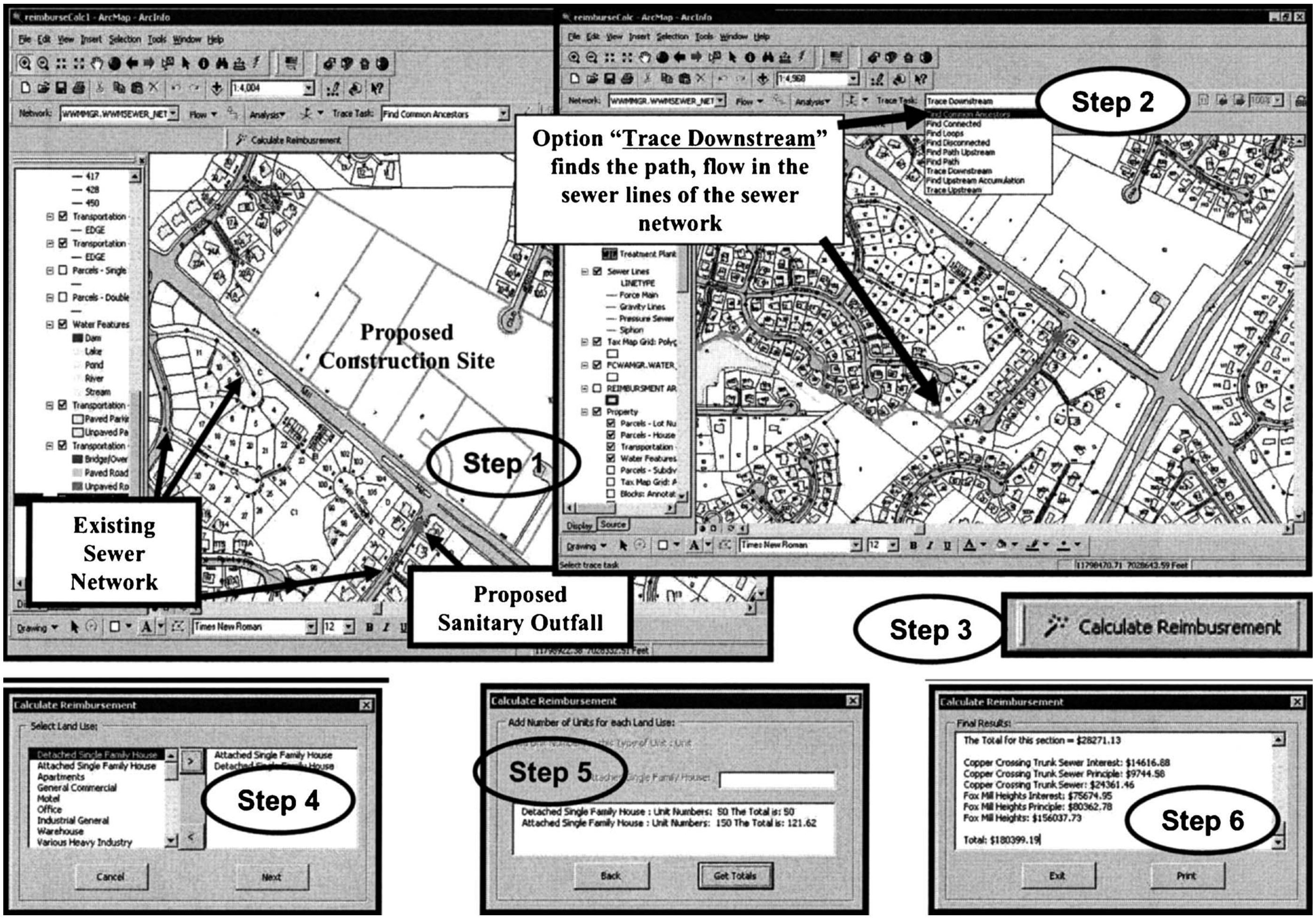

Fig. 5. Demonstration of the functionality of GIS-MSSR (Elmasri and Navathe 2000)

Functional Requirements of the Sanitary Sewer Reimbursement System

Functional requirement specifications capture the intended behavior of the system. This behavior may be expressed as services, tasks, or functions the system is required to perform. The following functional requirements outline the functionality of the GIS-MSSR.

1. The primary function of the GIS-MSSR is to serve the task needs of the sanitary sewer reimbursement process for new as well as existing developments. Additionally, the application should serve as a tool to analyze the downstream sewer utilization (length, flow capacity, etc.) from any manhole location in the sewer distribution network.
2. At a minimum, the application should access layers of GIS data on land parcel and utility network (road, sewer, and water network).
3. Sanitary sewer reimbursement processes and related practices in Fairfax County should be integrated into the model. These practices should be transformed into relational data tables that can be integrated with GIS data layers.
4. The user should be able to use the application in the form of an extension to the ArcGIS environment.
5. As the initial step in the computational process, the user shall initiate the sanitary sewer reimbursement task by identifying (flagging) the manhole as the outfall for the future sewer connection.
6. A pathfinding algorithm must be implemented to traverse the sewer network downstream of the outfall upon selecting an option: "**Trace Downstream.**"
7. Cost computations based on the sewer network utilization must be performed upon selecting an option: "**Calculate Reimbursement.**"
8. The user should be given an option to select land-use type (e.g., residential or commercial) and the number of housing units (e.g., number of detached housing units and townhouses).
9. Reimbursement calculations should be visually displayed for review and verification. Furthermore, the user should be given an option to print the computations, along with a map of the sewer network where sewer lines used by the new neighborhood are identified. The printout should be in the form of a notification letter from the county to the developer.

Development of GIS-MSSR

The logic pertaining to the entire sanitary sewer reimbursement process is represented as a flow chart (Baik 2004), which is then implemented as Visual Basic code inside the ArcView 8.2 development environment. The following five major modules outline the technical details of the tool GIS-MSSR and its inner workings.

Calculation Date :2/25/2004

Copper Crossing Trunk Sewer: Section 2
171.62 UNITS @ 8.24 per unit = $1414.15
Interest @ 10% from 6/18/1986 = $2121.23
The Total for this section = $3535.38

Copper Crossing Trunk Sewer: Section 1
171.62 UNITS @ 5.58 per unit = $957.64
Interest @ 10% from 6/18/1986 = $1436.46
The Total for this section = $2394.1

Copper Crossing Trunk Sewer: Section 5
171.62 UNITS @ 11.63 per unit = $1995.94
Interest @ 10% from 6/18/1986 = $2993.91
The Total for this section = $4989.85

Copper Crossing Trunk Sewer: Section 4
171.62 UNITS @ 8.49 per unit = $1457.05
Interest @ 10% from 6/18/1986 = $2185.58
The Total for this section = $3642.63

Copper Crossing Trunk Sewer: Section 3
171.62 UNITS @ 8.31 per unit = $1426.16
Interest @ 10% from 6/18/1986 = $2139.24
The Total for this section = $3565.4

Copper Crossing Trunk Sewer: Section 7
171.62 UNITS @ 5.22 per unit = $895.86
Interest @ 10% from 6/18/1986 = $1343.79
The Total for this section = $2239.65

Copper Crossing Trunk Sewer: Section 6
171.62 UNITS @ 9.31 per unit = $1597.78
Interest @ 10% from 6/18/1986 = $2396.67
The Total for this section = $3994.45

Fox Mill Heights: Section 3
171.62 UNITS @ 233.19 per unit = $40020.07
Interest @ 10% from 9/23/1994 = $37685.57
The Total for this section = $77705.64

Fox Mill Heights: Section 2
171.62 UNITS @ 150.23 per unit = $25782.47
Interest @ 10% from 9/23/1994 = $24278.49
The Total for this section = $50060.96

Fox Mill Heights: Section 1
171.62 UNITS @ 84.84 per unit = $14560.24
Interest @ 10% from 9/23/1994 = $13710.89
The Total for this section = $28271.13

Copper Crossing Trunk Sewer Interest: $14616.88
Copper Crossing Trunk Sewer Principle: $9744.58
Copper Crossing Trunk Sewer: $24361.46
Fox Mill Heights Interest: $75674.95
Fox Mill Heights Principle: $80362.78
Fox Mill Heights: $156037.73

Total: $180399.19

Reimbursement Calculation

Fairfax County, Wastewater Management

2/25/2004

To:

Subject: Reimbursement Areas
Copper Crossing Trunk Sewer
Fox Mill Heights

Dear Reader:

This is to advise that your proposed development is located in the above referenced sanitary sewer reimbursement area. As such, additional acreage charges over and above the normal availability fees will be due prior to issuance of plumbing permits for connection to sanitary sewer system.

The estimated charge is $ 180399.19
It should be noted that interest is to date and must be recomputed at the time of payment.

Please call me at 324-5186 if additional information is required.

Very truly yours,

Bo H. Baik, Engineer II
Engineering Analysis and Planning Branch

Fig. 6. Typical notification letter generated using GIS-MSSR

Module 1: Selection
1. User selects the land-use type of the new development from the land-use table.
2. The GIS interface user also selects the manhole at which sanitary outfall from the new development is connected.
3. The network analyst of ArcGIS is invoked to trace the downstream sewer lines of the sanitary sewer network line layer.

Module 2: Flow Conversion
User inputs are mapped into the land use and flow table and the flow rate is computed.

Module 3: Sanitary Sewer Reimbursement Program Details
1. The selection set of the sewer lines (from Module 1) is looped over.
2. The details of the sanitary sewer management program for all the downstream sanitary sewer lines are obtained (reimbursement amount, remaining life of the contract, etc.).

Module 4: Check Reimbursement
This module flags those sewer lines that are subject to reimbursement.

Module 5: Calculate Reimbursement
In this module, yearly reimbursement and interest are computed and output for all the sewer lines used by the new development.

The functionality of GIS-MSSR corresponds closely to the functional requirement specifications, and the working mechanisms of the model are illustrated in Fig. 5. Fig. 6 shows an official notification generated by the system for an actual reimbursement calculation.

Productivity Measures of Effectiveness for GIS-MSSR

The Bureau of Labor Statistics (BLS) of the U.S. Department of Labor defines productivity as the rate of output per unit of input. Productivity is difficult to measure because outputs and inputs are typically quite diverse and are themselves hard to measure. Individual measures of productivity can vary significantly across industries. For example, in a private enterprise, productivity can be measured by the ratio of revenue per employee, the return on assets, and at a more specific level, the number of widgets produced per hour at a given plant running with a given level of staffing, equipment, energy, and other inputs.

In measuring the productivity of the economy of a country, a simple and often-used measure of productivity is real gross domestic product (GDP) per person-hour worked in the economy. However, while real GDP is a good and comprehensive measure of total output, person-hours worked is, for many purposes, an inadequate measure of inputs because it neglects variations in the quality of labor and ignores other inputs, notably capital goods. Although more difficult to represent empirically, multifactor productivity is a better measure because it takes into account all factor inputs, not just labor (BLS 2005).

In many economic analyses of new projects, time and money saved by employing the new tool or method are often used as measures of productivity. In this section, an attempt is made to measure the productivity gains that can be realized by employing MSSR in Fairfax County engineering management functions. About 125 plans required sanitary reimbursement calculations in Fairfax County (in 2004). Each reimbursement calculation requires from 20 min to an hour; the average time required for a manual reimbursement calculation is approximately 40 min. Table 2 shows the staff time requirement and pay to estimate the total staff time and cost to process reimbursement estimations.

The total cost of all engineering staff members is about $68 per each reimbursement processing, which is equivalent to approximately $8,500 for 2004, where about 125 reimbursement computations were completed. This amount reflects only the actual services provided and does not account for additional reimbursement estimation that could have been requested due to availability of staff time. Time requirements for completing the process with the help of the GIS tool are significantly shorter than the time requirements for the manual operations. In terms of staff cost, the automated system will cost the county about $2.91 per reimbursement, or a cost saving of about $65 (95%) per reimbursement. This is a great example of how public money and staff resources can be saved using GIS.

It should be noted that the above time and cost savings did not take into account the cost of development of the GIS model in terms of developer time and resources used. The development of the model was done by plan review engineers for the county, who are also skilled in developing GIS tools. The development of GIS-MSSR is done purely for research and demonstration purposes rather than as a county-sponsored project. Should this be a county-sponsored project, the estimated cost of developing the model is about $5,600 (or one person-month of the developer's time).

The solution developed for this engineering management task is therefore expected to more than break even in the first year of its use. It should also be pointed out that all the hourly rates used in this comparison are unburdened rates; that is, no indirect costs are included. If the indirect costs are included, the cost savings are expected to be noticeably greater.

Conclusions

The state of the practice review indicated that most municipal governments have embraced GIS for administrative and some core engineering functions. It is determined that the use of GIS for engineering management service functions in municipalities across the United States is sparse for a variety of reasons. The approach and methodology discussed in this paper are focused on providing qualitative justification for EMSFs at municipal governments with a GIS environment. However, adapting this methodology to a sanitary sewer reimbursement program in Fairfax County, Virginia, demonstrated that substantial productivity gains can be realized when EMSFs are automated on GIS platforms. Most notable benefits of such automation are the reduction in turnaround time, which can translate to several thousand dollars in annual cost savings. In the public works departments within municipal governments across the country, several engineering management tasks related to urban infrastructure can be automated in a similar fashion. Though it is hard to quantify the productivity gains resulting from each operation, collectively a GIS-based engineering management system for municipal government can yield significant productivity gains.

It is believed that this demonstration will entice many municipal governments to rapidly embrace GIS for the needs of EMSFs. It should be pointed out that the applied nature of the research presented in this study is consistent with the nature of typical GIS undertakings for a variety of problems.

References

Abudayyeh, O., Cai, H., Fenves, S. J., Law, K., O'Neill, R., and Rasdorf, W. (2004). "Assessment of the computing component of civil engineering education." *J. Comput. Civ. Eng.*, 18(3), 187–195.

Baik, B. (2004). "Geographic information system in sanitary sewer system management." MS thesis, George Mason Univ., Fairfax. Va.

Borchardt, B., and Tonias, C. N. (1996). "Oklahoma City integrates engineering, surveying and GIS." *Public Works*, 127(8), 53–54.

Bowman, D. (1998). "Civil engineering meets GIS." *J. Comput. Civ. Eng.*, 12(1), 5–7.

Bureau of Labor Statistics (BLS). (2005). U.S. Dept. of Labor, Washington, D.C., ⟨www.bls.gov⟩.

Denning, J. (1993). "Small-government GIS." *Civ. Eng. (N.Y.)*, 63(6), 52–54.

Elmasri, R., and Navathe, S. B. (2000). *Fundamentals of database systems*, 3rd Ed., Addison-Wesley, New York.

Environmental Systems Research Institute (ESRI). (2005). "Special achievement in GIS." ⟨http://gis.esri.com/uc2003/sag/list/index.cfm⟩.

Herzog, M. T., and Labadie, J. W. (2000). *Stormwater and waste management*, ASCE, Reston, Va., 151–170.

Joshphar, K., Dasari, G. R., Phoon, K.-K., and Tan, T.-S. (2005). "Development of a Web-GIS based geotechnical information system." *J. Comput. Civ. Eng.*, 19(3), 323–327.

Lancaster County, Pennsylvania. (2005). "Geographic information systems." ⟨http://www.co.lancaster.pa.us/gis/cwp/browse.asp?A=3⟩ (July 2005).

Miles, S. B., and Ho, C. L. (1999). "Applications and issues of GIS as tool for civil engineering modeling." *J. Comput. Civ. Eng.*, 13(3), 144–152.

Murphy, C. (2000). "GIS trends." *Civil Engineering News*, December, 62–65.

Preusch, D. P., and Rezakhani, M. (1999). "Integrating geographic information systems (GIS) and watershed modeling." *29th Annual Water*

Resources Planning and Management Conf. E. M. Wilson, ed., Tempe, Ariz.

Pritchard, M. J. (2005). "Medina County Sanitary Engineers GIS." Medina County, Ohio, ⟨http://www.sanitaryengineer.co.medina.oh.us/map.html⟩.

Przybyla, J. (2002). "What stops folks cold from pursuing GIS?" *Public Works*, April, 36–42.

Sanghavi, S., and Mattejat, P. (2003). "Stormwater GIS: Managing state–wide stormwater BMPS." *Public Works*, July, 18–20.

Stidger, R. W. (2002). "Managing municipal streets." *Better Roads*, June, 22–25.

Turton, T. (2003). "Technology applications for planning and assessment." *Int. Conf. on Ecology and Transportation*.